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Incorporating estuaries as a source or sink of sediment within assessments of coastline risk and adaptation to climate change

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Abstract

Complex coastal landforms exhibit variable behaviour in response to sea-level rise. A proposed modelling framework that integrates shoreline changes associated with longterm recession, short-term variability and sea-level rise advocates that coastal risk assessment be undertaken within the context of a geomorphologically-based modelling framework whereby a coastline is subdivided into coastal compartments or cells, thereby recognising the sedimentary links between compartments. For example, the Narrabeen coastline includes bounding headland compartments, a bay compartment and an estuary compartment; and the behaviour of the coastline varies according to the response of each of these compartments to variable climatic and oceanic conditions. This approach is extended to other estuarine systems in southern NSW. Estuaries play an important role as a source or sink of sediment that varies widely in accordance with climatic and oceanic conditions. Accounting for the role of estuaries in coastline behaviour involves identifying the variable shorelines within estuaries; establishing the long-term estuarine shoreline behaviour and the response of shorelines to sea-level change; and integrating models that best represent the response of estuarine shorelines to climate change within the proposed integrated modelling framework for coastal risk assessment. Recognising the links between sedimentary sources and sinks and integrating models of estuarine behaviour with models of open coast behaviour will improve coastal risk assessment and provide greater confidence in adaptation options.

Keywords

sediment, incorporating, within, estuaries, assessments, coastline, risk, adaptation, climate, change, source, sink

Disciplines

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Incorporating estuaries as a source or sink of sediment within assessments of coastline risk and adaptation to climate change

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Abstract

Complex coastal landforms exhibit variable behaviour in response to sea-level rise. A proposed modelling framework that integrates shoreline changes associated with long-term recession, short-term variability and sea-level rise advocates that coastal risk assessment be undertaken within the context of a geomorphologically-based modelling framework whereby a coastline is subdivided into coastal compartments or cells, thereby recognising the sedimentary links between compartments. For example, the Narrabeen coastline includes bounding headland compartments, a bay compartment and an estuary compartment; and the behaviour of the coastline varies according to the response of each of these compartments to variable climatic and oceanic conditions. This approach is extended to other estuarine systems in southern NSW. Estuaries play an important role as a source or sink of sediment that varies widely in accordance with climatic and oceanic conditions. Accounting for the role of estuaries in coastline behaviour involves identifying the variable shorelines within estuaries; establishing the long-term estuarine shoreline behaviour and the response of shorelines to sea-level change; and integrating models that best represent the response of estuarine shorelines to climate change within the proposed integrated modelling framework for coastal risk assessment. Recognising the links between sedimentary sources and sinks and integrating models of estuarine behaviour with models of open coast behaviour will improve coastal risk assessment and provide greater confidence in adaptation options.

Introduction

Coasts occur at the interface between marine and terrestrial environments, and consequently are exposed to a range of climate drivers that operate in marine and terrestrial environments (Nicholls *et al.* 2007). These influence the way in which coastal morphology changes as well as the physiological response of species (Lough and Hobday 2011). The exposure of coastal landforms, ecosystems and settlements to these drivers varies depending on the nature of the coastal system. There has been much focus on how climate change, and particularly sea-level rise will affect open coasts; beach systems are largely influenced by marine climate drivers, such as altered sea level, waves and storm intensity and frequency. This contrasts with estuaries, the upper reaches of which are influenced primarily by terrestrial climate drivers, such as changes in runoff. The interaction of marine and terrestrial climate-related drivers is particularly evident in estuaries (**Error! Reference source not found.**) (Gillanders *et al.* 2011), but is likely to vary along the length of individual estuaries, as also will the influence of non-climatic drivers of change, such as landuse change, ecosystem degradation, pollution and invasive species (Rosenzweig *et al.* 2007). Commonly cited climate drivers include changes to sea level, air and sea temperature, increased precipitation and catchment run-off, changes in storm patterns and potential increase in the frequency, magnitude or extent of severe weather systems (NCCOE 2012; Roper *et al.* 2011). The interactions between climate drivers and existing processes may have secondary influences on coastal and estuarine processes, and the NCCOE identify 13 secondary process variables related to the primary climate drivers (Table 1).

Table 1: Primary climate drivers and secondary process variables influencing coastal and estuarine environments. Source NCCOE (2012).

Primary climate drivers	Secondary process variables
Mean sea level	Local sea level
Ocean currents and temperature	Local currents
Wind climate	Local winds
Wave climate	Local waves
Rainfall/runoff	Effects on structures
Air temperature	Groundwater
	Coastal flooding
	Beach response
	Foreshore stability
	Sediment transport
	Estuary hydraulics
	Water quality
	Ecology

Coastal hazard and risk assessments have typically focused on open coasts subject to marine climate drivers. However, along the New South Wales coast, many more people live on the margins of estuaries or other coastal water bodies than along the open shoreline. The impact of climate change will be felt differently within estuaries. Their response to climate change is mediated by estuary entrances which represent important linkages between open coasts, estuaries and terrestrial environments. It will be necessary to consider the complexity of estuarine shorelines and the processes controlling their morphology, in order to foreshadow changes that can be anticipated in future decades. In this paper we consider coastal morphology and its variation within estuaries, and whether estuaries are a source or sink of sediment which will ultimately affect their response to future changes in boundary conditions (such as sea level or rainfall/run-off) and hence require consideration in coastal risk assessments, whether of ecosystem dynamics or the vulnerability of settlements and infrastructure.

A framework for characterising the coast

Different coasts behave differently, and geomorphological setting provides the context within which to examine the vulnerability of an ecosystem or asset. Within a collaborative project through the National Climate Change Adaptation Research Facility (NCCARF), we have considered a range of probabilistic responses of Narrabeen Beach in northern Sydney to future sea-level rise (Woodroffe *et al.* in review). We characterised the Narrabeen section of coast adopting a coastal systems mapping approach that has been developed in the United Kingdom (Figure 2). Coastal system mapping can guide vulnerability assessments at a range of spatial scales by efficiently encapsulating geomorphic behaviour (Whitehouse *et al.* 2009), and provides a framework for predictive modelling. Coastal system mapping involves conceptualising a coastal system into discrete components and the identification of interactions between these components. In the case of Narrabeen, it is apparent that there is an important link between the dynamics of the beach and the transport of sand into the mouth of Narrabeen Lagoon. The inlet sequesters sand; indeed sand is periodically removed from the inlet entrance and returned to the beach as part of beach replenishment. Sea-level rise, and other climate drivers, can be anticipated to have impacts around the margin of Narrabeen Lagoon. In this paper, we examine how this framework can be extended to consider the vulnerability of ecosystems and infrastructure around other estuaries in southern NSW, outlining some preliminary findings that have developed from a related NCCARF project.

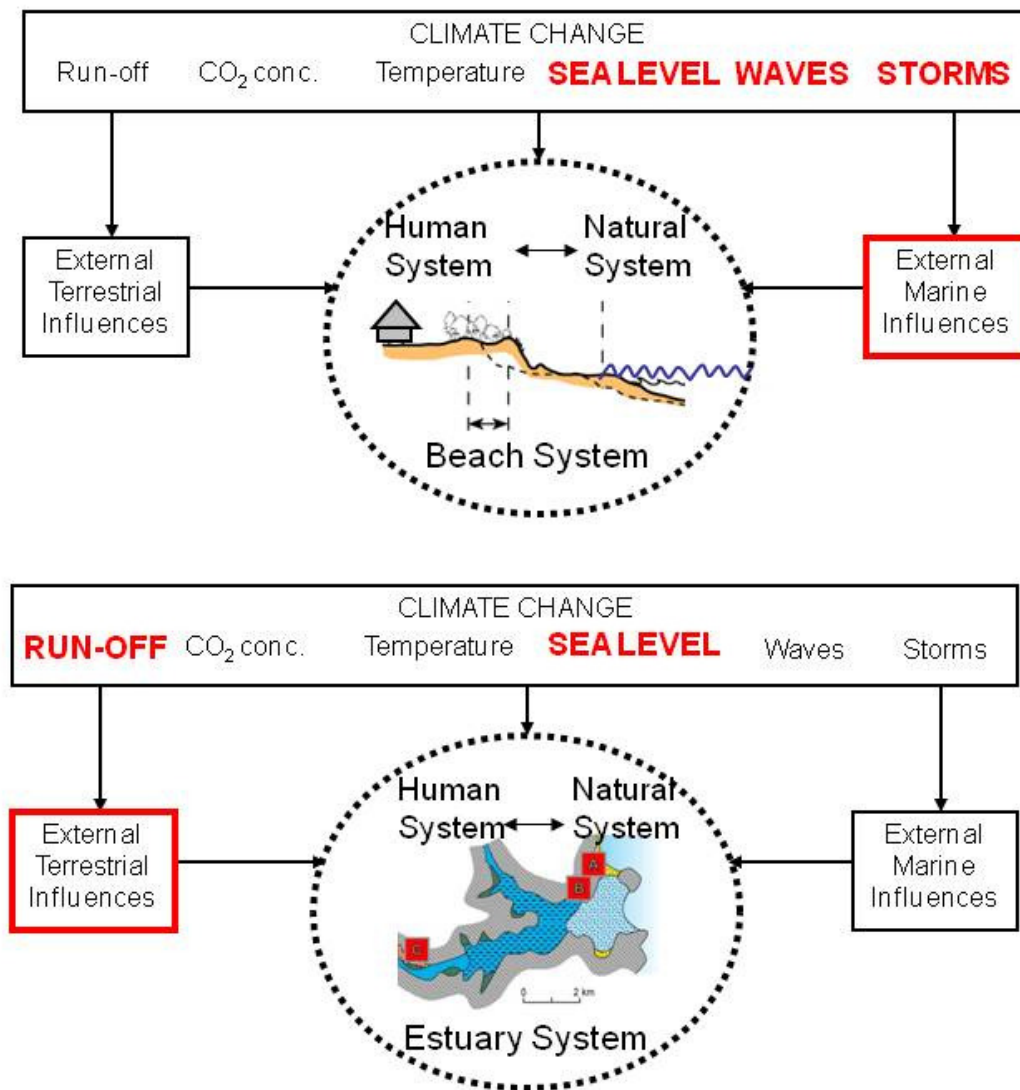


Figure 1: The principal climate drivers that influence coastal systems (after Nicholls *et al.* 2007), emphasising how these may affect beach systems and estuary systems differently. The most prominent drivers are shown in capitals.

Estuaries of southern NSW; their origin and evolution

Estuaries are generally defined as a semi-enclosed coastal waterbody where marine waters are diluted by freshwater (Pritchard 1967). Potter *et al.* (2010) qualify the conditions of an estuary to incorporate all possible salinity and hydrological scenarios in which estuaries occur globally. In this case estuaries are defined as “a partially enclosed coastal body of water that is either permanently or periodically open to the sea and which receives at least periodic discharge from a river(s), and thus, while its salinity is typically less than that of natural sea water and varies temporally and along its length, it can become hypersaline in regions when evaporative water loss is high and freshwater and tidal inputs are negligible.” Consistent in all definitions is the concept that an estuary is a coastal waterbody that is confined to some extent. Importantly, this waterbody acts as accommodation space for many abiotic and biotic components and processes. At the broadest sense, the estuary is a zone where marine water and freshwater derived from catchments merge. These waters transport

sediment from the marine and terrestrial environments where they are deposited or redistributed to other environments and these sediments provide substrate and nutrients for the development of biota and ecosystems that are unique to estuarine environments.

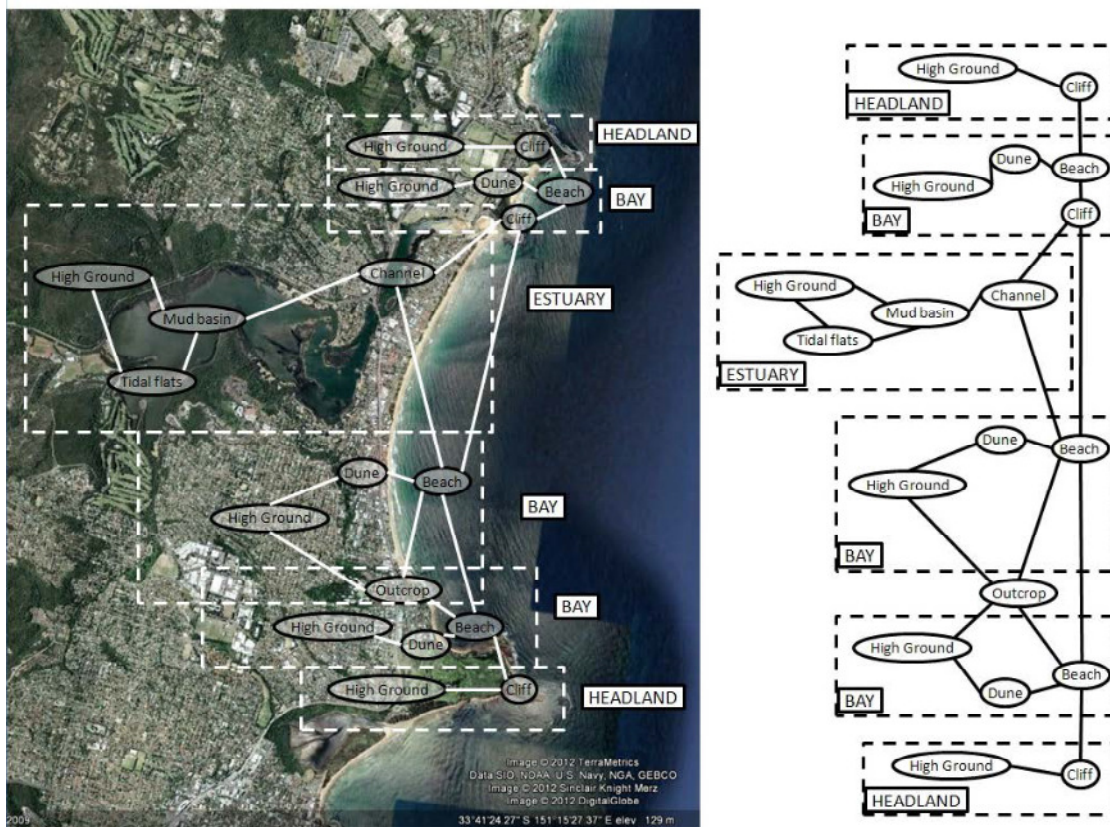


Figure 2: A preliminary characterisation of the Narrabeen compartment and the interactions between the different landform components of the entire system (from Woodroffe *et al.* in review), adopting the type of conceptualisation (left) and topological representation (right), advocated in the UK (Whitehouse *et al.* 2009).

The estuaries of southern NSW originated in incised bedrock (or drowned river) valleys on a wave-dominated coastline. Due to the overriding influence of wave energy, sand barriers and spits develop at estuary entrances and act to restrict wave and tide energy at the entrance. Geomorphic classifications of the estuaries of Australia recognise the influence of waves on estuary morphology, but also account for the varying contribution of river and tide power on estuary morphology (Harris and Heap 2003; Harris *et al.* 2002; Kench 1999; Rochford 1955; Roy 1984; Roy *et al.* 2001). Classifications focussed on the wave-dominated coastlines of southeastern Australia. (Roy 1984; Roy *et al.* 2001) give greater consideration to the accommodation space provided by estuaries and the role of river, wave and tide energy on estuarine infill over time. Consequently, this scheme recognises four evolutionary stages for wave-dominated estuaries: youthful, intermediate, semi-mature and mature (Figure 3).

Youthful barrier estuaries and coastal lagoons of southern NSW (described fully in Roy *et al.* 2001) comprise (in an east to west direction) a marine zone with an entrance barrier and marine tidal delta predominantly composed of marine sand deposited as sea-level rose during the most recent post-glacial marine transgression (~7000ka); an estuarine zone including the central mud basin, which is the low energy, largely unfilled portion of the previously incised bedrock valley; fluvial zone where estuarine and fluvial

processes merge and the alluvial zone, which is largely freshwater dominated and includes alluvial floodplains composed of terrigenous sediment delivered to the incised bedrock valley. The net result of this youthful morphology is that the estuary acts as a sink for sediment and water; the barrier and flood tide delta accommodate marine sands delivered to the estuary from the adjacent marine environment and wave energy limits the transport of material from the estuary to adjacent marine environments; the attenuation of tides in the broad central mud basin ensures that any entrained fine marine material is deposited; while diminishing river energy in the central mud basin ensures that colluvial and alluvial material is deposited on floodplains and fluvial deltas and muds are deposited in the central mud basin.

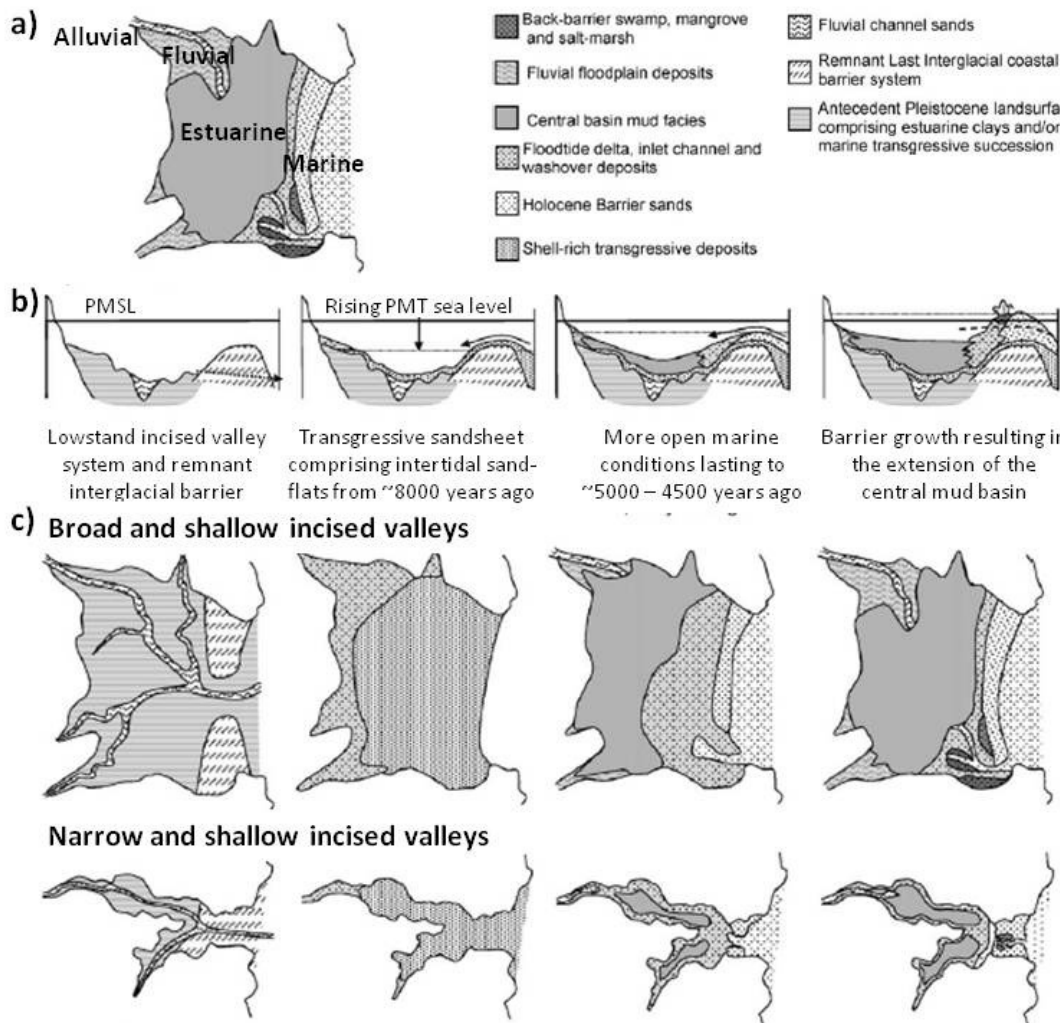


Figure 3: a) Estuary zonation including the marine, estuarine, fluvial and alluvial zones; b) Estuary evolution indicating decreasing accommodation space as sea level rose and the estuarine zone infilled with sediment; c) Bedrock valley shape and the variability in accommodation space between broad and narrow valleys as they mature. Source: Sloss *et al.* 2006; Adapted from Roy 1984.

By contrast mature estuaries (described fully in Roy *et al.* 2001) which comprise a well developed barrier and flood tide delta, which may extend into marine regions to produce an ebb-tide delta; a central mud basin that has been almost completely infilled by sediment sourced from marine and terrestrial environments, causing fluvial flows to be directed through a channel with dimensions constrained by fluvial volumes; and well-developed alluvial plains that almost entirely fill the incised bedrock valley. As these wave-dominated estuaries infill river and tide power is increasingly less

attenuated; tidal influence extends landward and ebb-tide deltas form seaward of existing barriers; and in the case of large mature estuaries, river power may extend seaward, enabling the export of material into marine environments. The net result of this mature morphology is that the estuary has little accommodation space and increasingly acts as a source of sediment to adjacent marine environments.

The primary difference between these extremes of estuary evolution is the accommodation space provided for sediment and water inputs. This accommodation space is partially controlled by the shape of the original incised bedrock valley. Research conducted at the University of Wollongong has attempted to build upon the classification of Roy (1984) and Roy *et al.* (2001) by accounting for the variable shape of the bedrock valley. For example, estuaries located within broad, shallow incised valleys, such as Lake Illawarra and St Georges Basin, exhibit greater accommodation space than those located in narrow incised valleys, such as Burrill Lake and Lake Conjola (Sloss *et al.* 2006; Sloss *et al.* 2009) (Figure 3), despite exhibiting the same intermediate evolutionary stage and developing under the same environmental conditions (see Roy *et al.* 2001 for evolutionary stage). This relationship between accommodation space and valley shape also holds true for mature estuaries such as Shoalhaven River (broad valley) and Minnamurra River (narrow, incised valley) (Haslett *et al.* 2010; Panayotou *et al.* 2007; Woodroffe *et al.* 2000). As a consequence of limited accommodation space, marine influences are greater in narrow valleys than in broader incised valleys where barrier deposits are concentrated near the entrance (Sloss *et al.* 2005).

Estuaries and sediment budgets

The relationship between rates of sediment supply and rates of sea-level rise is central to understanding the geomorphic response of estuaries to climate change. Surplus or deficits of sediment from a shoreline or estuary over a period are regarded as the 'sediment budget' (Rosati 2005). A positive sediment budget occurs when sediment gained on a coastline exceeds the sediment lost over a period, with the net result being shoreline progradation or shoreline elevation increase; conversely, regression at the geological scale, or erosion at the event scale, is associated with a negative sediment budget. Sediment budget contributions for a typical estuary can be considered in terms of sediment 'inputs', 'outputs' and sediment exchange occurring within the estuary or 'within-system transfers' (Table 2). The main sediment inputs and outputs can vary depending on the overriding influence of river, wave and tide energy within an estuary. In the context of sea-level rise an increase in the sediment budget for an estuary is required to maintain the relationship between shoreline elevations and water levels within estuaries.

Table 2: The main sediment budget contributions for a typical estuary. Adapted from Townend and Whitehead (2003).

Inputs	Within-system transfers	Outputs
Marine influx Fluvial influx Littoral drift	Saltmarsh erosion/accretion Mangrove erosion/accretion Intertidal erosion/accretion Subtidal erosion/accretion Organic matter contributions Total mass of suspended sediment in system Dispersion/disturbance from dredging Vessel induced erosion of intertidal or subtidal Cliff erosion	Efflux to sea Offshore placement of dredge spoil

Depositional environments in estuaries are artefacts of positive sediment budgets occurring under stable sea-level conditions over the mid to late Holocene (and in some cases during the Pleistocene). Efficient trapping of sediment and evolution towards 'maturity' is largely driven by rates of sediment supply from the catchment and marine environments and the hydrodynamics within an estuary. Hence mature estuaries exhibit a strongly positive sediment budget, with rates of sediment supply tending towards equilibrium with sea-level rise, while immature estuaries exhibit weakly positive sediment budgets, with sediment supply lagging behind rates of sea-level rise. Analysis of contemporary sediment budgets provides valuable information for quantifying the response of estuaries to projected sea-level rise in the 21st century.

Consequences of climate change to estuaries in southern NSW

Sea-level rise acts to reverse estuary evolution and increases the areal extent of open water and intertidal areas within estuaries, thereby creating accommodation space for the deposition of marine sands and terrestrial colluvial deposits, muds and silts. Due to strong hydrological links between the ocean and estuaries (and even intermittently open estuaries or ICOLLs), base and maximum water levels within estuaries are projected to increase at rates equivalent to sea-level rise (Haines and Thom 2007). The geomorphic response of estuaries to sea-level rise, evident through increased accommodation space, will vary in accordance with a number of factors.

Estuary maturity. The stage of infill is an artefact of sediment budgets occurring over the Holocene; accordingly, mature estuaries have strongly positive sediment budgets, while immature estuaries have weakly positive sediment budgets. Should these antecedent conditions continue in the future, mature estuaries may continue to infill at rates that approach equilibrium with the rate of increase in accommodation space (i.e. sea-level rise); conversely, sediment delivery to immature estuaries may lag the rate of increase in accommodation space. Extensive marine transgressive deposits that extend further landward in some estuaries in southern Australia support the hypothesis that rates of sediment supply to barriers may lag rates of sea-level rise (Sloss *et al.* 2005). These deposits provide evidence that lower estuaries have behaved more like marine embayments during the mid Holocene, with the estuary only becoming confined when rates of sediment supply exceeded rates of sea-level rise. In addition, estuary maturity can also denote possible areas impacted by sea-level rise. Low-lying depositional environments are poorly developed in immature estuaries and tend to be confined to the fluvial delta and flood-tide delta regions, while low-lying alluvial plains are extensive on the margins of mature estuaries. Consequently, settlements, infrastructure and agriculture that favour the environmental conditions on alluvial plains (e.g. flat topography and nutrient rich alluvial soils) are vulnerable to inundation and flooding.

Shape of the bedrock valley. Accommodation space provided by sea-level rise is proportional to the shape of the bedrock valley with greater accommodation space created in broad, shallow valleys compared to narrow confined valleys. In the absence of enhanced sediment budgets, alluvial plains and estuarine plains on broad valleys will be more sensitive to inundation from sea-level rise, flooding and storm surge than shallow incised valleys.

Estuary zonation. Estuary zonation will inform the exposure of depositional environments to climate drivers, and consequently the exposure of associated ecosystems, settlements and infrastructure. The marine zone, which includes the barrier, tidal creeks and flats, tidal deltas and back barrier sand flats, will preferentially be exposed to marine climate drivers such as wave climate and sea level, while the fluvial and alluvial zones, which includes floodplains, levees, distributary channels and the flood-tide delta, will preferentially be exposed to terrestrial climate drivers such as rainfall/runoff. Exposure of the estuarine zone to climate drivers will be partly mediated

by estuary maturity and the shape of the bedrock valley. This concept is illustrated schematically in Figure 4 which shows how settlements located in different positions in an estuary might be vulnerable to different impacts associated with climate change. For example, a town located on a fluvial delta, of the alluvial floodplain in a wave dominated estuary is unlikely to be exposed to storm surges, but increased rainfall and runoff may elevate the risk of flooding; however, a settlement located on the sand barrier or at an estuary entrance is more likely to be exposed to storm surge and washover.

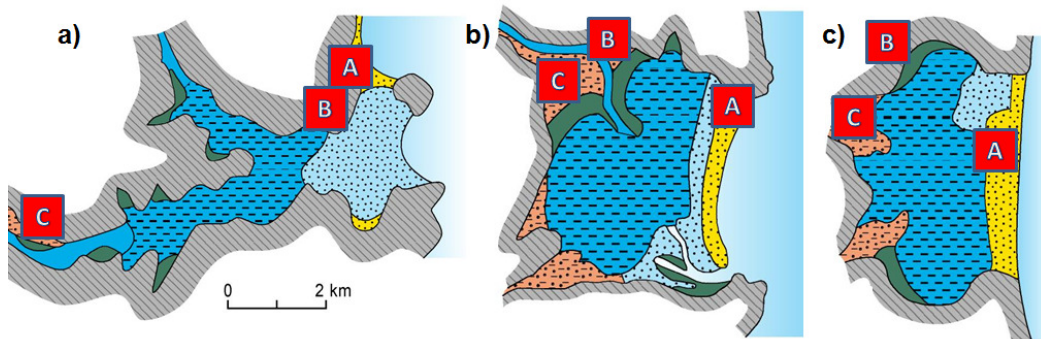


Figure 4: Schematic example of the principal types of estuary in southern NSW: a) drowned river valley, b) barrier estuary and c) ICOLL, and the location of different settlements: A on the sand barrier, B on the bedrock margin of the estuary, and C on the fluvial delta. The relative exposure to impacts from different climate drivers could be described for towns in these different settings, under different future scenarios.

Utility of estuarine geomorphology in coastal vulnerability assessment

The Intergovernmental Panel on Climate Change define climate change vulnerability as a function of exposure, sensitivity and adaptive capacity (Parry *et al.* 2007) and estuarine geomorphology provides a useful foundation from which to assess the vulnerability of coastal assets, such as settlements, infrastructure and estuarine ecosystems, to climate change at a range of spatial scales. At larger spatial scales of assessment (e.g. whole of estuary) estuary zonation, shape of the bedrock valley and maturity provide valuable contextual information about the exposure, sensitivity and adaptive capacity of an estuary, respectively. Exposure is largely driven by the spatial variability in climate drivers over a study region. This may be assessed by using a template or interactions matrix (Abuodha and Woodroffe 2006). A simple template was proposed by NCCOE (2004) as a framework for assessing exposure to primary and secondary climate drivers (Figure 5), and its use is re-affirmed by the revised guidelines proposed by NCCOE (2012). Estuaries within broad shallow valleys exhibit greater sensitivity to impacts from climate change, such as inundation, storm surge and flooding, than those in narrow incised valleys, while mature estuaries exhibit greater capacity to adapt to climate drivers than immature estuaries. Hence, assuming no change in long-term sediment budgets and excluding the variability in climate drivers of the region, the estuaries most vulnerable to climate change in southern NSW are immature estuaries within broad shallow valleys, such as Lake Illawarra and St Georges Basin.

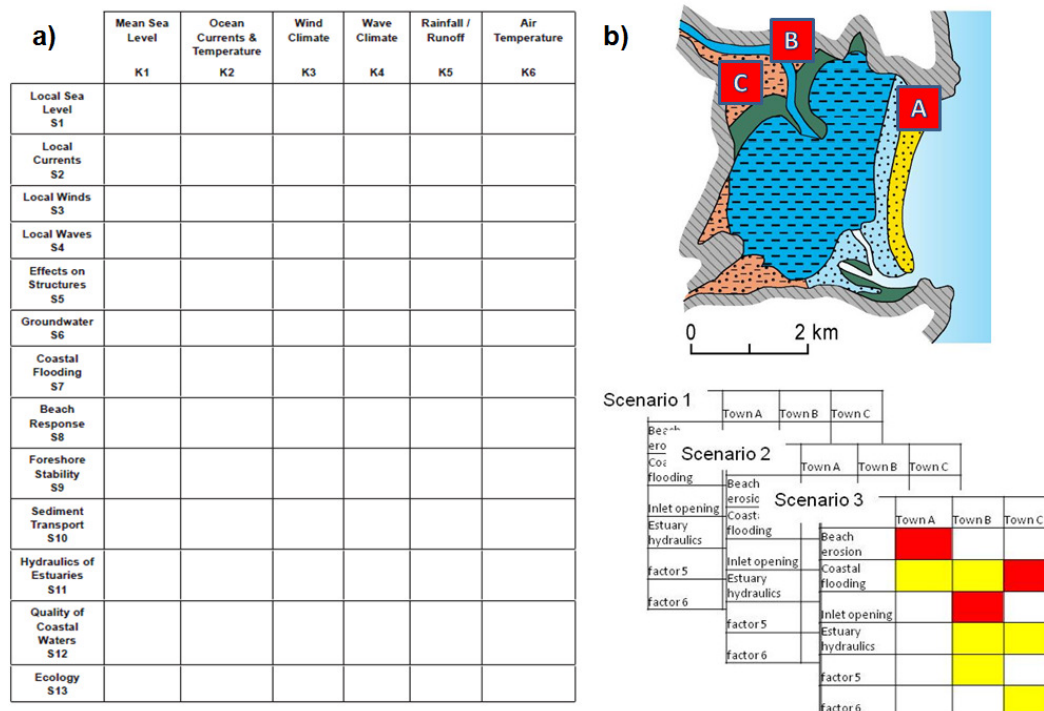


Figure 5: a) An interactions matrix, such as that proposed by NCCOE (2012), is a useful tool for assessing the exposure of coastal assets to climate change. b) The matrix can be applied to assets located within different estuarine zones including A on the barrier, B on the bedrock margin of the estuary and C on the fluvial delta.

At smaller spatial scales (e.g. shorelines within an estuary) exposure of an asset can be established by considering the shape of the bedrock valley, whereby exposure diminishes as elevation and slope increase. Spatial analysis using Geographic Information Systems and high resolution Digital Elevation Models, such as those derived from LiDAR, are valuable tools for rapidly identifying exposure at this scale; however finer scale analysis, such as topographic profiles or surface elevation measures, may be required for dynamic shorelines (e.g. beaches, intertidal wetlands). The sensitivity of an asset can be guided by the surrounding geology and soils, whereby shorelines composed of soft sediments (e.g. muds and sands) are more sensitive to erosion and reworking than rocky shorelines. The adaptive capacity of an asset can be guided by the natural occurrence, or absence, of depositional shorelines within an estuary (e.g. mangrove, saltmarsh and intertidal flats), which indicates the sediment budget of the estuary over geological timescales.

Case study: Comparison of Wagonga Inlet and Minnamurra estuary

Wagonga Inlet (36°13'15"S, 150°7'45"E) has a relatively small and steep catchment (94 km²) that includes the township of Narooma. Slopes exceed 10° throughout much of the catchment, with gentle slopes located within vicinity of the inlet. As a consequence the catchment is largely regarded as non-arable and remains forested (Bodalla State Forest) with grazing limited to the gentle slopes near the estuary. The estuary is classified as an immature barrier estuary (type 3A; Roy *et al.* 2001) with an open entrance, though this is maintained through training and dredging. The ingress of marine sediment over the past 6000 years resulted in the development of a barrier, known as Bar Beach, at the entrance of the estuary, and extensive shoaling and flood-and ebb-tide deltas. The main estuary body is relatively deep with an average depth of approximately 6 m. Steep shoreline slopes elsewhere within the estuary prevent extensive development of tidal flats, except where the tributaries deliver sediment to

fluvial deltas. Mangrove and saltmarsh are now largely confined to these small fluvial deltas at the margins of the estuary; though analysis of the Quaternary geology reveals that much of the township, particularly in the Narooma Flats area, is low lying and situated upon a mature part of the flood tide delta (Figure 7).

At the estuary scale, coastal system mapping (Figure 6) emphasises the linkages between the steep catchment and the estuary, and the complex flood tide delta, entrance, channel and barrier processes. It also highlights the sediment sinks (e.g. tidal flats, mud basin, dune, beach) and sources (e.g. beaches, bay and high ground), and depositional components (e.g. tidal flats, beaches) that may require detailed analysis of their response. Due to the situation of the township upon estuarine sediments, the Narooma Flats area is particularly sensitive to climate drivers, though training walls may buffer (or deflect) some of the effects and act to build capacity. As the estuary is relatively immature and the ingress of marine sediments is limited by engineering works, such as training walls and dredging, the adaptive capacity of the estuary may be limited. As a consequence, the vulnerability of Narooma is particularly high due to the combined influence of the exposure of the township to climate drivers, the sensitivity of low-lying erodible soils on which much of the township is located (Figure 7) and the limited adaptive capacity in terms of sediment delivery to the estuary.

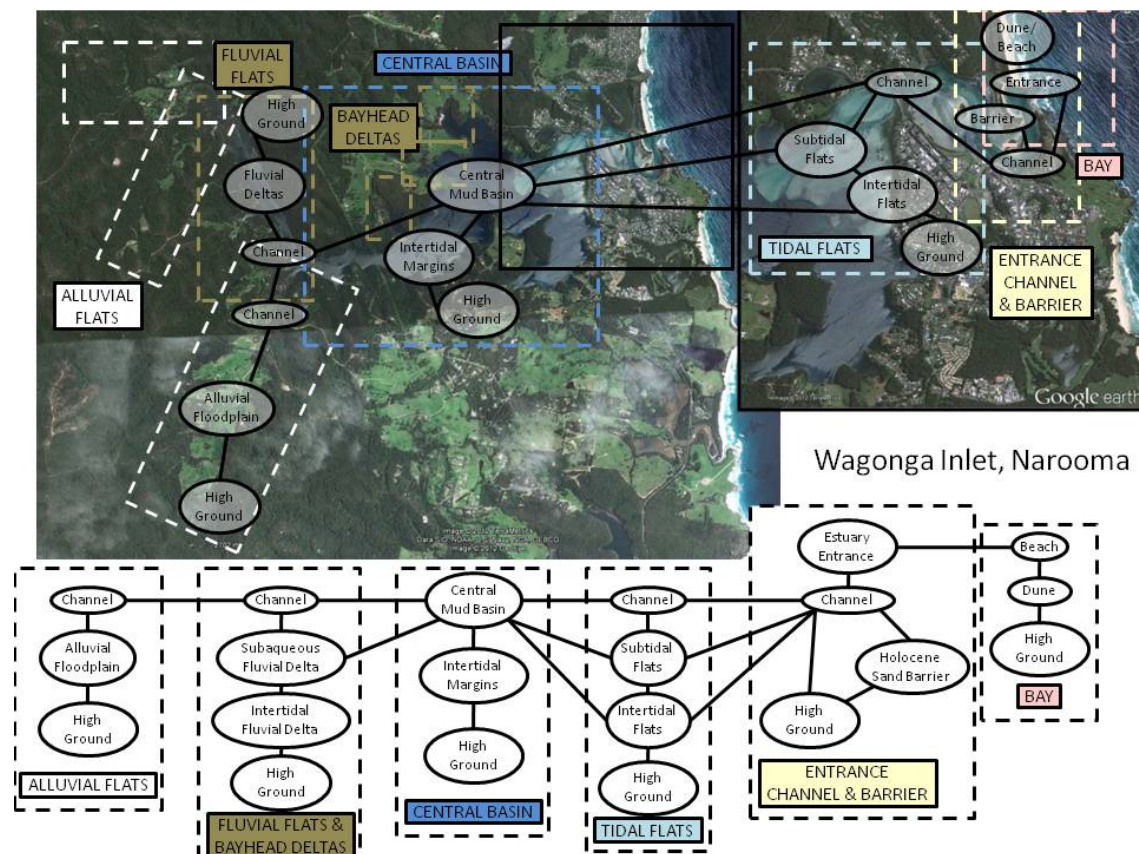
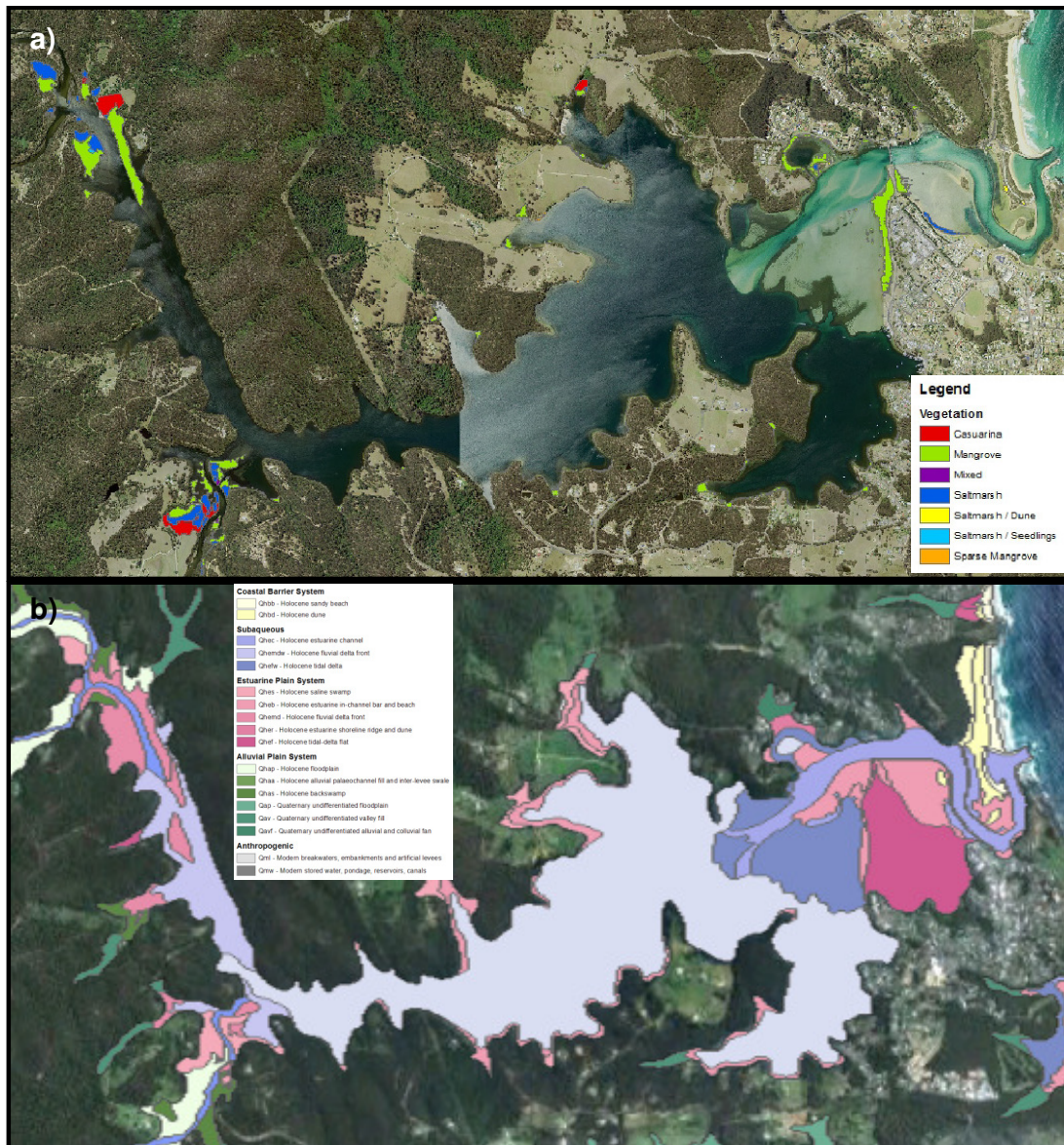


Figure 6: Coastal systems mapping for Wagonga Inlet.



The immature stage of infill of Wagonga Inlet contrasts with the Minnamurra estuary which has been almost completely infilled (type 3D, Roy *et al.* 2001). The Minnamurra estuary (34°37'00"S, 150°51'10"E) lies within a relatively small, confined catchment (142 km²) and includes the township of Minnamurra. The floodplain is constricted between relatively steep catchment slopes to the north and south, and the floodplain and slopes are now largely used for dairy farming. The entrance of Minnamurra River is partially protected from waves by Stack Island and the township of Minnamurra is situated upon the barrier (Figure 8). Coring through the Terragong plains reveals that there was a central mud basin 4-5000 years ago, which had accreted to form the swampy plains of Terragong swamp by around 3000 years ago (Panayotou *et al.* 2007). Whereas this upper estuary was characterised by estuarine habitats in the past, at present there are relatively few intertidal habitats and mangrove and saltmarsh are restricted to limited riverside locations in the lower estuary (Figure 8). Sedimentation has been continuing beneath these intertidal wetlands and historical change

determined from aerial photography indicates gradual expansion of mangrove landwards into saltmarsh (Chafer 1998; Oliver *et al.* 2012). Detailed analysis of surface elevation and sedimentation within mangrove and saltmarsh at Minnamurra estuary has been used to project the broad pattern of change using several simulation models and the upper and lower bounds of projected sea-level rise scenarios (Figure 9).

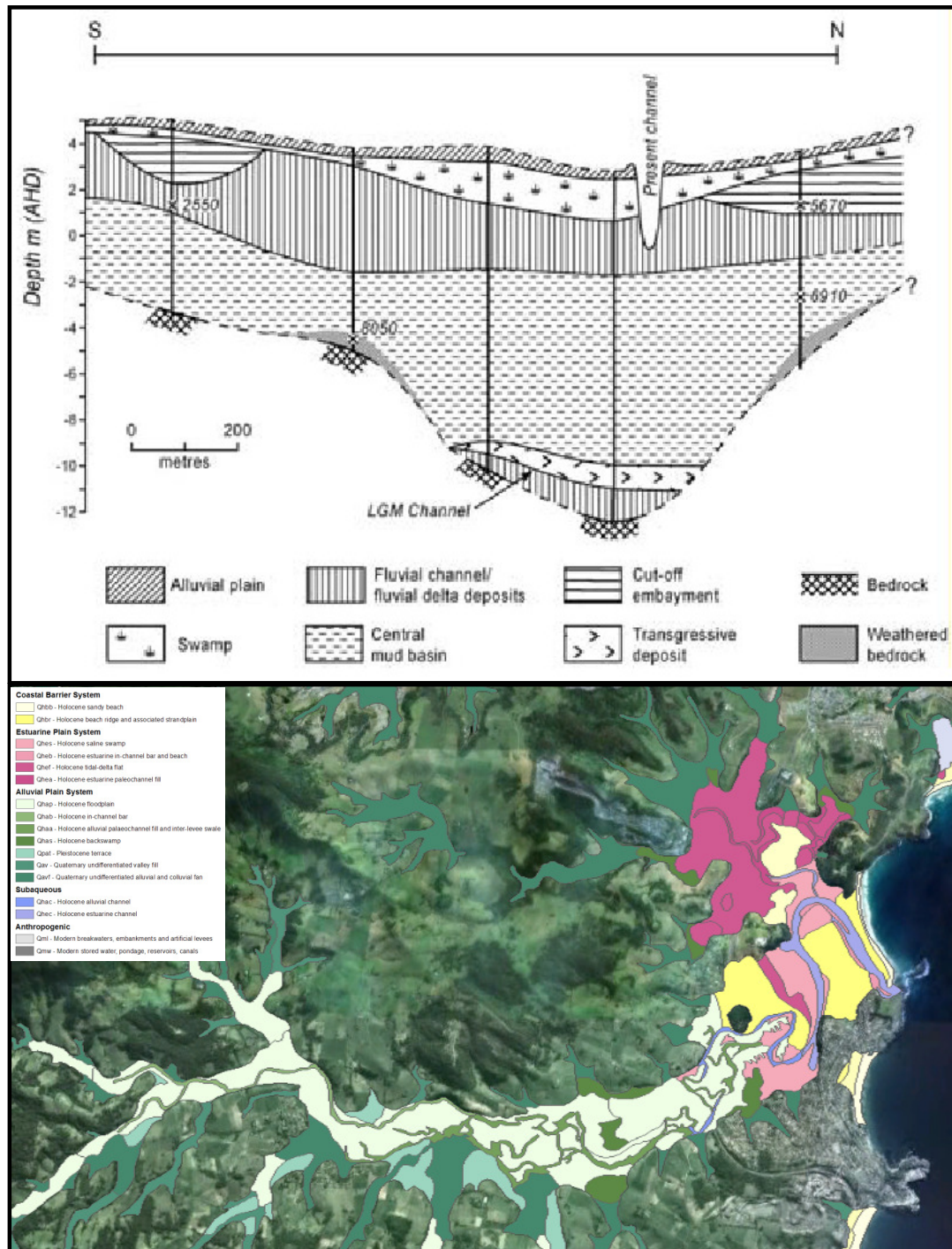


Figure 8: Historic sediment budgets at Minnamurra River were informed by: a) stratigraphic evidence from estuarine depositional environments; and b) the mapped distribution of Quaternary geology depositional facies. Sources: Panayotou *et al.* (2007), Troedson *et al.* (2004).

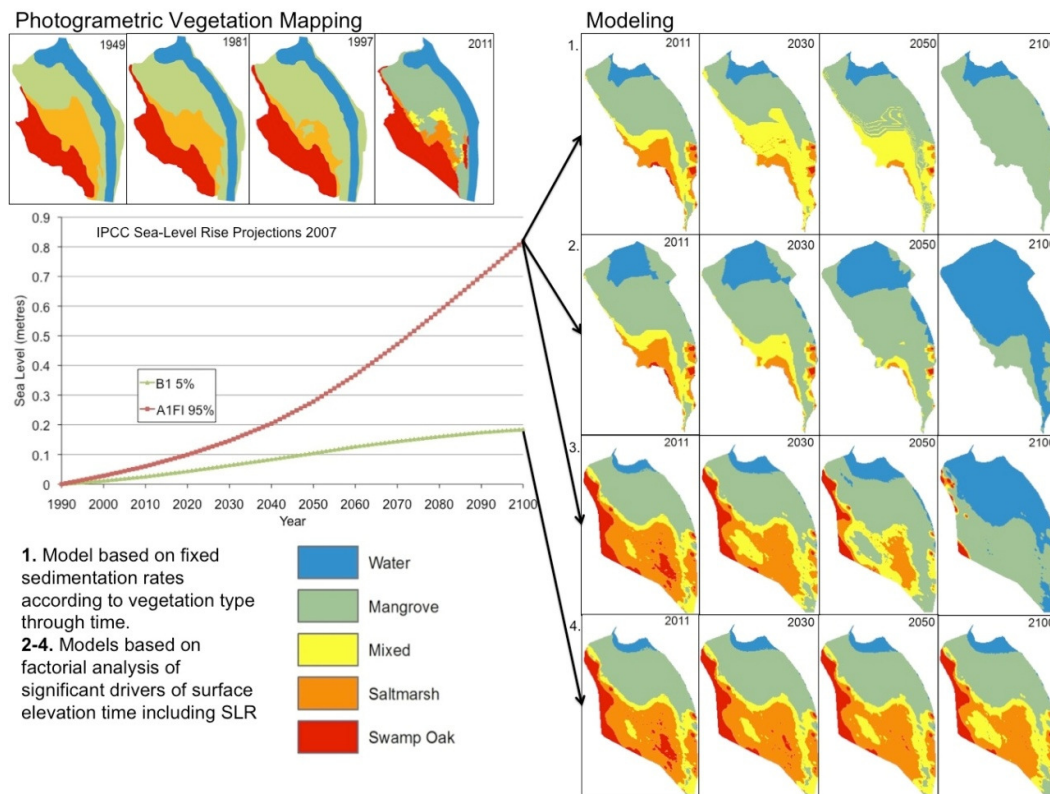


Figure 9: A summary of changes to wetland vegetation at a monitored mangrove-saltmarsh site in the Minnamurra estuary. The upper left shows historical changes in vegetation distribution derived from aerial photographs, and the right hand panels show projected future distribution based on 4 different models and sea-level scenarios (based on Oliver et al., 2012).

The hydrological implications of climate change for these two estuaries will differ. For example, sea-level rise in the Minnamurra estuary may eventually result in tidal penetration further upstream, and the plains that have been drained and have sustained a dairy industry may be subject to overtopping, tidal creek incision, or saline intrusion. The absence of extensive alluvial plains at Wagonga Inlet limits the influence of tidal penetration on alluvial plains. In addition, the expansive water area and steep catchment slopes of Wagonga Inlet may readily accommodate high catchment runoff volumes; in the Minnamurra estuary low-lying alluvial plains may increasingly accommodate catchment runoff.

It would be possible to adapt the models used in Figure 9 to Wagonga Inlet. What is apparent from Figure 9 is that different models suggest different patterns of future change and are very sensitive to underlying assumptions. At this stage the models assume unlimited sediment supply, and that wetlands will accrete vertically into the accommodation space that results from sea-level rise. Incorporating a sediment budget component into the modelling would add a greater degree of sophistication to the modelling. In the case of Wagonga Inlet, which can be inferred to have a relatively limited sediment input from fluvial sources given its immature stage of infill, and which has a large accommodation space that includes the extensive central mud basin as well as a considerable intertidal zone around the margin, it would seem likely that less sediment would be available to become sequestered in mangrove or saltmarsh substrates. In such a case these habitats might show a lesser ability to keep-up with sea level rise with recession of the wetland shoreline and a decrease in the total wetland area likely.

Conclusions

Coastal risk assessments commonly focus on marine related climate drivers; however estuaries create important linkages between open coasts and terrestrial environments; hence estuaries, and associated settlements, infrastructure and ecosystems, are exposed to the full-range of climate drivers occurring in marine and terrestrial environments. The response of estuaries to climate drivers is complex; individual estuaries, and indeed shorelines within estuaries, behave differently and we propose that some of this variability, particularly at geological timescales, can be explained by differences in estuary geomorphology. In particular, estuary zonation, maturity and shape of the bedrock valley can mediate the response of estuaries to climate drivers; and consequently, analysis of these factors provides valuable information about the vulnerability of an estuary, or estuarine shoreline, to climate change. The proposed geomorphic framework for assessing broadscale vulnerability of estuaries can be used to prioritise further detailed assessment of vulnerability within an estuary, such as the example provided at Minnamurra River. However, due to the complexity of estuaries, we also propose that further research be directed towards improving modelling and assessment techniques to incorporate variability in sediment budgets and estuary hydrology.

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